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# RESEARCH MEMORANDUM

CHARACTERISTICS OF A TRANSONIC TEST SECTION WITH

VARIOUS SLOT SHAPES IN THE LANGLEY

8-FOOT HIGH-SPEED TUNNEL

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SUMMARY


A large wind tunnel, approximately eight feet in diameter, has been
converted to transonic operation by means of slots in the boundary
extending in the direction of flow.  The usefulness of such a slotted
wind tunnel, already known with respect to the reduction of the sub-
sonic blockage interference and the production of continuously variable
supersonic flows, has been augmented by devising a slot shape with
which a supersonic test region with excellent flow quality can be pro-
duced.  The uniform Mach number in the test region is infinitely variable
up to supersonic Mach numbers without change of tunnel geometry.  The
power required for operation of the slotted tunnel is considerably in
excess of that for the closed tunnel but could be somewhat reduced.
The flow principles involved in the operation of such a wind tunnel
are discussed in some detail.


INTRODUCTION


In reference 1, a type of wind tunnel having a slotted test section
is described for which the tunnel boundary interference due to solid
blockage can be greatly decreased or reduced to zero and in which tunnel
choking does not exist.  The stream Mach number in the slotted test
section can be varied continuously up to and through a value of 1.0 and
the Mach number in the supersonic range is, moreover, continuously
variable.  In order to take advantage of these favorable characteristics,
the Langley 8-foot high-speed tunnel was converted to slotted-tunnel
operation early in 1950.  The present paper describes this modification
and the subsequent changes necessary to produce a test region with
uniform Mach number.  Little analysis is attempted beyond that which
was required to obtain a qualitative understanding of the manner of

operation of the tunnel and to effect the needed changes.  Preliminary indications of the character and uniformity of the flow in the test section are given.

## DESIGN OF TEST SECTION

The modification of the Langley 8-foot high-speed tunnel was limited by the desire to preserve intact the original reinforced concrete structure.  The length available for the test section was therefore restricted to the 15-foot-long region between the downstream end of the entrance cone and the upstream end of the diffuser; the maximum transverse dimension could not exceed the approximately 96-inch minimum diameter of the entrance cone and diffuser.  Because, moreover, of the necessity of taking into the diffuser the low-speed air from the mixing region at the slots and because of the expansion required for supersonic flow, the cross-sectional area at the throat had to be reduced to a value less than that at the diffuser entrance, about 20 percent less as suggested by the experiments of reference 1.

In order to accomplish this reduction of area at the throat, a liner was inserted into the original tunnel.  The liner and test section were made polygonal in cross section to facilitate construction and to provide plane surfaces for windows.  The twelve-sided regular polygon was chosen as it provided a sufficiently near approach to the circular cross section of the entrance and diffuser to make enough space available for the supporting structure at all points between the original entrance cone and the liner and to allow the fairing into the circular diffuser entrance to be relatively easy.  The sides were sufficiently wide to accommodate windows approximately twelve inches square. A cut-away view of the installation is  shown in figure 1.

The shape of the entrance liner, given in figure 2, was based on that of the plaster nozzle described in reference 2.  This entrance shape, which near its downstream end diverged to an angle of 5 minutes with the center line of the tunnel, was designed to produce a very gradual expansion, so that the Mach number at tunnel station 0 (origin for tapered slots) is closely uniform and, for all supersonic test-section Mach numbers, is equal to unity all over the cross section. The boundary-layer development is responsible (see reference 2) for the fact that the effective minimum section (cross section at which the Mach number is unity) exists at or near the slot origin rather than 32 inches upstream at the geometrical minimum section.  With this liner the maximum possible ratio of diffuser-entrance cross-sectional area to throat cross-sectional area is about 1.18.

The test section was made of steel panels reinforced on the back and supported at the ends. Between the panels, at the corners of the polygon, slot spaces were left sufficiently wide to permit the attachment of strips forming rounded slot edges. By changing these slot edges, constructed of wood to facilitate their modification, various slot shapes (plan forms) could be tested. The spaces between the panels were made sufficiently wide to permit slot widths considerably in excess of that width corresponding to a total opening of one-ninth of the periphery, which is the ratio of open to total jet boundary judged from reference 1 to be required (with 12 equally spaced slots) for zero solid blockage. Some of the slot shapes tested are shown in figure 3. For the rectangular shape (number 10) originally designed, the edges were made of steel, and two of these edges contained rows of pressure orifices. Figure 4 shows the locations of these and other orifice rows. The pressure orifices at the center were located in the axial survey tube shown in figure 1.

In the original design, windows were placed in three panels on each side of the test section, but in assembly, in order to facilitate model observation, one of these glazed panels was interchanged with the top panel, (fig. 1, section C-C).

The panels were originally installed with a divergence angle relative to the center line of the tunnel of 45 minutes. To reach this divergence from the 5-minute divergence at the downstream end of the approach section, the upstream end of every panel was gradually curved over the first 18 inches. The shape of this curved region is shown in figure 5(a).

The stream-side surfaces of the panels and of the downstream 10 feet of the entrance cone were carefully machined, and precautions were taken to assure the smoothness and continuity of the surface. In particular, considerable care was exercised to minimize any differences in surface level at the juncture between the panels and the entrance cone. Inaccuracies in window installation caused disturbances which were removed by fairing the edges or by reinstallation.

At 125.6 inches from their upstream ends the panels joined with a transition section (fig. 5(a)) which led into the circular diffuser entrance at the 180-inch station. This transition section was made up of curved elements and flat triangular parts as shown in figure 1. The triangular flats made an angle of approximately $2^\circ 30'$ with the center line of the tunnel so that a discontinuity in slope existed at the 125.6-inch station. The transition section was slotted but the slots could be filled and thus stopped at any position between the 125.6- and 180-inch stations. Because the panels were of essentially constant width, the slot width in this divergent region increased from 2.6 inches to about 3.5 inches.

As indicated in figure 1, section C-C, the structure of the panels was such that open channels existed under the slots. Because of the turbulent mixing at the slots and of the expansion to supersonic flow, the jet must expand into the channels. Continuity then requires, since the chamber surrounding the slots is sealed, that air which came out through the slots must reenter and pass into the diffuser. In order to guide this air into the diffuser entrance, noses were placed in the channels at the downstream ends of the slots as shown in figure 5. Several different nose shapes were tried, the first of which is indicated in figure 1. The nose shape used for most of the tests discussed in this paper is shown in figure 6(a). This nose could be moved upstream or downstream to match the position of the downstream end of the slot. A later modification, including side plates which restricted the downstream channel width, was designed to reduce the power consumption, (fig. 6(b)). The flap (fig. 6(b)), which was open for subsonic operation and closed for supersonic operation, was designed to relieve a subsonic negative Mach number gradient introduced into the test region by this nose shape.

The original dome-shaped test chamber was used as the sealed tank surrounding the slots, (fig. 1). This chamber was adequately large, having a maximum diameter of 40 feet. It nowhere approached the slotted test section closer than 6 feet. Glass observation ports were provided in the top, at one side, and in the chamber door. The large size of test chamber permitted location of the schlieren system inside the pressure chamber; thus greater flexibility of movement (from one window to another) was provided and introduction of thick glass into the light path was obviated.

PRELIMINARY INVESTIGATIONS

Inasmuch as the modified 8-foot high-speed tunnel was the first large slotted tunnel constructed at the Langley Laboratory, the first task was to study its general characteristics. Such a study was facilitated by the large size of the test chamber, which permitted direct observation during tunnel operation from positions near the slots. Such observation was limited, however, by the noise, which became painful at Mach numbers greater than about 0.6, and by the danger of a sudden large pressure increase due to power failure at large Mach number, which might result in physical injury to the observer. The test chamber was also uncomfortably hot because of the necessity of operating the tunnel with high stagnation temperature, up to 180° F, in order to prevent condensation difficulties.

In an investigation of the noise, the natural fundamental frequency of the test-chamber - slot system was roughly estimated at about 3 cycles per second. Measurements of the frequency and intensity of

the sound in the test chamber indicated a vibration with about this
frequency, but the greater part of the energy was rather widely dis-
tributed in general noise. This noise, which arose from the tunnel
fan, from the vorticity and general turbulence in the slots, and from
the general diffuser flow, reached an intensity in excess of 130 decibels
at Mach numbers near unity. In addition, sections of the test-chamber
floor vibrated, apparently with their natural frequencies, but these
vibrations were not excessive. To minimize noise and vibration, blunt
diffuser entrance noses are believed to be desirable, because sharp
noses might be expected to produce oscillations when struck by the
vortices proceeding downstream just outside the slots.

In addition to the vibration, a general circulatory movement of the
air in the test chamber was observed. The scrubbing action at the slots
entrains air from the test chamber and carries it along toward the dif-
fuser entrance, whence it is separated from the tunnel flow at the dif-
fuser entrance noses, deflected out into the surrounding chamber, and
circulated back toward the upstream ends of the slots.

The first tests were made with the rectangular slot shape and with
a panel divergence of 45 minutes. The indicated Mach number distributions
at the various orifice rows are shown in figure 4. In this figure $M_{TC}$
is the Mach number corresponding to test chamber pressure. The total
pressure for these and all other Mach number distributions presented in
this paper is that near the center of the tunnel stream.

The Mach number distribution shown in figure 4 is evidently unsatis-
factory for model testing. As pointed out in reference 2, the flow dis-
turbances in a circular tunnel are concentrated at the center; as might
be expected the 12-sided tunnel with regular polygonal cross section
behaves in a similar manner, that is, the Mach number oscillations shown
in figure 4 are considerably greater near the center of the tunnel than
at the center of a panel. Special care is therefore required to obtain
a model test region with uniform Mach number. The solution to this
problem was deduced from tests with various slot widths and shapes,
from additional tests which had previously been carried out in the
apparatus of reference 1, and from a fundamental conception of the part
to be played by the slots in producing the supersonic flow. Previous
tests had already led to the belief that one of the most important
causes of the Mach number oscillations was the overexpansion in the
upstream part of the slotted section, similar to that which occurs when
a supersonic jet debouches into a region having a pressure less than
that at the jet exit. The function of the slot shape is conceived to
be the control of this expansion in such a way that the Mach number will
gradually approach its final test section value without exceeding this
value at any section. With the 45-minute divergence of the panels such
control was found to be impossible, although a number of different slot

shapes were tried, because the flow expansion produced by the curvature
and divergence of the panels already exceeded that required.

The possibility existed of removing most of this divergence by
turning end-for-end that part of the panels between stations 0 and
125.6 inches.  This modification as accomplished is shown in figure 5(b).
The panels are straight for the first 107 inches with slope 5 minutes
continuous with that of the entrance cone.  The curved part of the
plates now lies between the 107- and 125.6-inch stations; and curved
liners have been added between the 125.6- and 141.6-inch stations in
order to relieve the discontinuity in slope at that station and thus to
prevent large flow disturbances with attendant shocks in this region.

The efficacy of changing the panel divergence from 45 to 5 minutes
is shown in figure 7.  A considerable reduction in the Mach number
oscillations has been obtained, particularly near the center of the
tunnel.  The slot is now fulfilling its function of controlling the
development of the supersonic flow, and changes in slot shape might
therefore be utilized to improve the Mach number distribution at the
center of the tunnel.


INVESTIGATION OF SLOT SHAPES


The establishment of supersonic flow suitably uniform for model
testing in the slotted region of the Langley 8-foot high-speed tunnel
was the primary purpose of this investigation, since the production
of satisfactorily uniform flow at speeds up to and slightly exceeding
the speed of sound was easily achieved simply by the installation of
rectangular-plan-form slots.  (See fig. 8.)  The performance of rec-
tangular slots, reported in reference 1 for the case of a 12-inch-
diameter throat, was verified experimentally in the 88-inch effective-
diameter throat of the Langley 8-foot high-speed tunnel.  A charac-
teristic feature of supersonic flow in this type of slotted throat
equipped with rectangular slots is a rapid initial expansion and a
subsequent compression of the flow immediately downstream of the slot
origin.  At Mach numbers greater than about 1.02 disturbances associated
with the initial expansion-compression appear in the slotted-test-section
flow, and the magnitude of the disturbances increases with Mach number.
This performance is illustrated in figure 8 which presents the results
of flow surveys in the 8-foot tunnel with rectangular slots and with
the throat-geometry configuration of figure 5(b).  The disturbances
shown in figure 8 are sufficiently severe to preclude the use of
rectangular-plan-form slots at supersonic speeds in this test section.

The use of tapered slots to reduce the rapidity of the initial flow
expansion and the severity of the accompanying disturbances, which was

originally reported in reference 3, was followed in investigating suitable slot shapes for the Langley 8-foot high-speed tunnel. For this investigation the tunnel throat geometry of figure 5(b) was maintained. For some of these tests, the curved liner shown in figure 5 was replaced by a "boat-tail" as indicated at the top of figure 9, but this change did not significantly affect the flow in the test section. The first slot shape investigated was a straight-taper design, somewhat similar to one for which fairly good flow characteristics were reported in reference 3. This slot shape is identified in figure 3 as shape 1. The slot originated as a point at the effective minimum section of the tunnel (station 0) and opened with an angle of 0.77° between the edge and center line of the slot. The tapered portion extended 96 inches (1.09 jet diameters) downstream, after which the slot width remained constant. In this region of constant slot width, the open portion of the boundary comprised approximately one-ninth of the total periphery of the tunnel wall. The flow characteristics of the slotted section equipped with slot shape 1 (see fig. 9) corresponded approximately to those for the tapered slot reported in reference 3 for a 12-inch-diameter tunnel throat. The supersonic flow in both tunnels attained approximately the same maximum and minimum Mach numbers at equivalent distances (jet diameters) downstream of the slot origin. The existence of the compression region following the initial expansion was sufficient, however, to justify investigating the control of slotted-section flow characteristics by means of slot-shape modifications.

Other tapered slots were then investigated in an attempt to reduce the initial flow overexpansion and the compression that followed. The flow characteristics for slot shapes 4 and 9 which opened with only about half the angle of slot shape 1 over the first 48 inches downstream of the slot origin (see fig. 3) are shown in figures 10 and 11, respectively. Comparison of these data with those for slot shape 1 indicated that the reduction in the initial rate of opening of the tapered slot produced a corresponding reduction in the rate of flow expansion; also, the slight overexpansion and following compression of the supersonic flow produced by slot shape 1 was practically eliminated by use of shape 9. The flow expansions produced by slots 4 and 9 were almost identical in spite of the fact that slot shape 4 opens much more abruptly downstream of the 48-inch station. In the test section the degree of flow uniformity was slightly less for shape 4 than for shape 9, and it is therefore surmised that small flow-uniformity gains may be expected by changing the slot shape gradually over the downstream portion of its taper.

Slot shapes 6 and 7 (see fig. 3) utilized over their first 12 inches of length essentially the same initial taper angles employed for shapes 9 and 1, respectively; but following this 12-inch straight-taper region slots 6 and 7 opened with greater angles of divergence than did shapes 9 and 1 and attained their full-open widths at 76 and 74 inches downstream

of the slot origin. The results of flow surveys for these slot shapes
presented in figures 12 and 13, revealed that the supersonic flow
downstream of the initial straight-taper region expanded more rapidly
and compressed more severely than did the flow for slot shapes 9 and 1.
The data for slot shapes 1, 9, 6, and 7 indicated that, for tapered
slots whose initial opening angles are no greater than the 0.77-degree
half-angle taper used for shape 1, the important factor in controlling
the flow expansion and compression is the proper shaping of the slot
over the long region in which most of the opening to full slot width
takes place.

Slot shape 8, which opened in a straight taper of 1.18° half angle
over its first 48 inches from the slot origin (see fig. 3), produced
the Mach number distributions shown in figure 14. The supersonic-flow
expansion occurred more rapidly for slot shape 8 than for any of the
other tapered shapes investigated, as might be expected from the greater
angle at which it opened. At the higher Mach numbers the distribution
became saddle-shaped.

From the center-line Mach number distributions corresponding to
slot shapes 1, 4, 6, 7, 8, and 9, the possibility now existed of relating
slot-shape changes to the corresponding Mach number changes and thereby
effecting modifications designed to improve the distribution. For the
direction and a qualitative indication of the magnitude of the slot-width
changes required, the conception of the function of the slots in producing
the supersonic flow served as a guide. Thus, for instance, if at some
point along the center line the flow has expanded to a Mach number in
excess of that indicated by the test-chamber pressure, this overexpansion
can be traced back along a Mach line to a region on the tunnel boundary;
if in this region the pressure on the panels is greater than that in
the test chamber, a decrease in slot width is indicated in order to
reduce the flow expansion at that section.

In selecting a slot shape to serve as a basis for the new design,
shape 9 was chosen because it already produced a supersonic flow of con-
siderable uniformity. In addition to the changes intended to improve
the flow uniformity, which were accomplished by interpolating among
the slot shapes previously tested and by applying the ideas discussed
in the previous paragraph, a further modification was made in order to
decrease the length required for establishment of the uniform flow.
For this purpose the angle of taper at the upstream end was increased to
a value approaching that for shape 8. This increase in taper angle at
the upstream end was consistent with a decrease between the 55- and
75-inch stations, where such a decrease was believed to be desirable in
order to decrease the Mach number oscillations in the test region.
The final slot shape is shown as number 11 in figure 3.

The results of the flow surveys with slot shape 11, which are pre-
sented in figure 15, show a slight improvement in flow uniformity at
Mach numbers greater than 1.1.  The overexpansion with subsequent com-
pression is practically eliminated, and, moreover, this uniform flow is
reached in a shorter distance than with slot shape 9.  The length of the
essentially gradient-free region available for testing purposes varies
from about 80 inches at a stream Mach number of 1.07 to approximately
40 inches at a stream Mach number of about 1.13.  Extensive surveys,
including static-pressure measurements at axial intervals as close as
one-fourth inch, in the slotted section equipped with tapered slot
shape 11 indicate Mach number deviations no greater than those shown in
figure 15.  In a typical model-testing region approximately 36 inches
long and 30 inches in diameter, the Mach number deviations increased
with Mach number to values not exceeding ±0.006 at a stream Mach number
of 1.13.  This degree of flow uniformity was considered satisfactory for
model-testing purposes.

The coordinates for slot shape 11 are given in figure 16.  Also
included in this figure is the approximate shape of the slot edge which
was slightly over 0.5-inch thick and which remained essentially the
same for all of the slot shapes investigated.  Immediately outside the
slot edges, the channel between the edges and the test chamber opened
abruptly as indicated in section CC of figure 1.  If the thickness of
the slot edges and the size of the channel immediately outside the slot
opening had been greatly different, the characteristics of the flow
through the slots might have been influenced sufficiently to have
resulted in a final slot shape somewhat different from shape 11.  The
large size of the channels results in the maintenance of the pressure
just outside the slots at a value very close to that in the test chamber;
and the thinness of the slot edges tends to reduce the inertia effects
due to flow in the slots, which might aggravate the oscillation in the
test region.  The rounding of the slot edges may not be necessary, but
was taken as a precaution against disturbances that might arise from
flow separation at sharp corners.

Surveys so far obtained indicate that the quality of the flow in
the slotted test section with slot shape 11 is fully equal to that in
the most carefully designed two-dimensional solid nozzles.  This result
is the more remarkable when it is realized that the slot shape was
reached without the benefit of any such theory as is available for the
solid nozzle design and that, moreover, this uniform flow test region
is attained in a tunnel of approximately circular cross section, for
which the solid nozzle design is particularly critical.  It seems
reasonable therefore to conclude that for the slotted nozzle the design
is much less critical than for the solid nozzle.  This easing of the
design requirements is perhaps due to the fact that the slots in con-
junction with the panels produce an effective integrated damped elastic

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pressure boundary in contrast to the unyielding solid boundary of the solid nozzle. This pressure boundary is incapable of supporting the large pressure gradients that can exist at a completely solid boundary and, therefore, all disturbances at the boundary tend to be spread out into shallow oscillations instead of being concentrated into shocks as may occur in a solid nozzle.

In other respects the flow in the slotted nozzle is similar to that in a solid nozzle. Thus, just as in a solid nozzle, irregularities on the solid surfaces produce disturbances extending into the interior of the flow. Disturbances produced by strings 0.010 inch in diameter on the top and bottom panels at a Mach number of 1.074 are shown by the schlieren photograph inset in figure 17. These disturbances are propagated along lines at angles very close to the Mach angle. This behavior corresponds with the assumption, involved in the derivation of the slot shapes, that the only part of a slot effective at a point of the flow is that upstream of the intersection of that slot with the upstream Mach cone through the point.

GENERAL DISCUSSION

The theory of the subsonic operation of the slotted test section has been presented in reference 1. It is of interest at this point to consider in a qualitative manner some features of the supersonic operation. As pointed out in reference 4, the supersonic flow in a tunnel with porous walls is established by expansion through the walls. In a slotted tunnel a similar expansion must occur through the slots, but this expansion must be influenced by the boundary layer on the panels. In fact, a general knowledge of the behavior of boundary layers indicates that in the expansion the boundary layer tends to run off the panels into the slots. The effects of the slots must thus be extended over the whole periphery of the tunnel. It therefore seems that the slotted tunnel would behave more like the porous-wall tunnel than might at first be supposed. The role of the slots in controlling the expansion has already been noted.

The development of the supersonic flow in the slotted test section will now be considered in detail. At subsonic speeds the pressure in the test chamber evidently must take a value which is some weighted average of the pressures at the slots. Moreover, in accordance with the equation of motion, as the pressures in the diffuser (including that at the diffuser entrance) are decreased, the speed in the tunnel must increase until a Mach number of 1.0 is reached at the effective minimum section, section B-B in figure 1. Consider first the case of wall-panel divergence of 45 minutes. With the first attainment of Mach number 1.0 at the minimum section, the Mach number in the slotted

test section has been found to be also essentially 1.0, as is shown for a different divergence angle in figure 8; but on the curved surfaces of the panels (fig. 5(a)) supersonic regions terminated by shocks resulting from the higher pressures in the slots must already have appeared in conformance with general flow theory. The flow within the slotted test section is thus not absolutely uniform, but consists of slightly supersonic regions terminated by shocks, which are in turn followed by slightly subsonic regions. This flow pattern can be repeated several times because in any subsonic region the pressure may be greater than that in the chamber surrounding the slots. Equalization of the pressure through the slots thus accelerates the flow, and if the panel is curved in that region or if a change in shape occurs, the flow may again become supersonic.

When the pressure at the diffuser entrance is decreased (by increasing the rotational speed of the tunnel fan) below that just necessary to produce Mach number 1.0 at the throat, the pressure decrease cannot be transmitted upstream through the supersonic regions in the slotted test section. This pressure decrease is, however, transmitted out through the slots in the region just upstream of the diffuser entrance. The pressure in the surrounding chamber is thus decreased and, as a result of the reaction through the upstream part of the slots, the flow in the subsonic regions is further accelerated, the shocks are moved downstream, and the supersonic regions are expanded.

This movement of the shocks downstream has been noted in schlieren observations. If the curvature and divergence of the panels are small, only a small decrease of pressure below that required for the establishment of Mach number 1.0 at the throat is sufficient to sweep the shocks out of the test section. In such a case one shock only may exist. With the configuration of figure 5(a), this shock is located slightly downstream from the discontinuity in slope at the 125.6-inch station. It is evidenced in figure 4 by a rather sudden decrease in Mach number to values less than 1.0 occurring between the 130- and 140-inch stations. At this position the shock extends across the whole central part of the flow. In all the upstream slotted test section the stream Mach number is then greater than 1.0. At the upstream end the boundary layer flows out, so that the stream is allowed to expand, as it must do if the Mach number is to increase from the value of unity at the throat to some greater value somewhat downstream. This outward flow must evidently be balanced by an equivalent rate of mass flow into the slots near their downstream ends. Perhaps because of induced velocities due to flow through the slots, the pressures (indicated by Mach numbers in fig. 4) near the slot edges are less than those near the center of a panel, and the test chamber pressure lies generally between these two extremes.

Except for the improvement in control of the expansions obtainable
by means of the slots, which has already been mentioned, the manner of
operation of the slotted test section with 5-minute divergence is similar
to that with 45-minute divergence. However, because with the 5-minute
divergence the curved region of the panels is located at the downstream
end, the shocks must first form at that end, leaving the upstream end
essentially shock free, even at Mach numbers near unity. An indication
of this freedom from shock disturbances was afforded by limited schlieren
observations and is indicated in the Mach number distributions (figs. 8
to 15). With the 5-minute divergence of the panels the shock-disturbed
Mach number range near unity is thus eliminated, and uniform test sec-
tion Mach numbers continuously variable through 1.0 are possible.

The conditions at the downstream end of the slotted section will
now be considered. In this region for the configurations discussed in
this paper, the air flow which has been extruded from the upstream part
of the slots must be taken back into the tunnel stream. Because of the
turbulent mixing with the air in the chamber surrounding the slots,
this extruded air has lost most of its kinetic energy; but once this
air has re-entered the slots, it is again accelerated by mixing with the
main stream. This mixing process is believed to be accelerated by
vorticity generated by inflow over the slot edges.

The mixing is known to be at best an inefficient process and must
in any case entail a power loss; but even greater power losses may occur
if, because of the intake of this low-energy air, the diffuser flow is
spoiled. Conditions are necessarily particularly critical near the
diffuser entrance both because of the inflow of the low-energy air and
because in this region the kinetic energy of the main stream is large.
Because of the mixing (ejector principle) some diffusion would occur in
this region even if the expansion angle of the diffuser were zero.
Indeed the mixing is so strong that as may be seen from figures 8 to 15
the diffusion starts even slightly upstream from the diffuser entrance
noses.

Because of space limitations the original expansion angle at the
upstream end of the diffuser was made greater than was considered desir-
able and, when the panels were reversed, this angle was increased still
more, to 3°45' as shown in figure 5(b). In the region of the diffuser
entrance noses the effective expansion is somewhat less than this value
because the upper surfaces of the noses fall outside the panel sur-
faces (fig. 5). At some sacrifice of test section length, nose shape B
(fig. 6(b)), which extended farther upstream, furnished a short region
of essentially constant effective cross-sectional area at the beginning
of the diffuser. Such a length of essentially constant or only slightly
varying diffuser area is believed to be desirable in order to provide
a mixing region without too great diffusion, but no investigations have

been conducted to determine the proper length or divergence of such a
region for minimum power.

The need for a length of diffuser at small or zero expansion near
the diffuser entrance is accentuated by the presence of the shock.  In
reference 2, it was shown that in such a region the boundary layer behind
a shock terminating the test region at a Mach number of 1.2 recovered
rapidly without separation.  In a diverging channel, on the other hand,
such a shock might easily lead to separation.  The shocks indicated at
the diffuser entrance in figures 8 to 15 appear to be oblique rather
than normal shocks, since the greater disturbance occurs at the center
and that at the wall is spread out and does not decrease the indicated
Mach number below unity.  The use of a region of zero expansion at the
diffuser entrance should spread these disturbances still farther and
may very well effect their practical elimination.

The shock at the diffuser entrance is similar to one which might
exist ahead of a nose inlet.  Because the high-speed flow is limited
to a jet, however, it should be possible to draw the shock down into
the diffuser, but in this case the power required would almost certainly
be greater than if it were close to the diffuser entrance.  The most
favorable configuration, for minimum power, is believed to be that for
which the shock stands just inside an essentially zero-divergence region
at the diffuser entrance or has been practically eliminated in the mixing
region.

The minimum diffuser entrance cross-sectional area constitutes, in
effect, a second throat.  If this second throat is too small the flow will
be choked and the Mach number attainable will be limited.  Because of the
thick boundary layer formed by the inflow through the slots the required
area of the second throat is greater than would be necessary for a closed
nozzle with the same size of first minimum.  With increase in supersonic
Mach number the required area of second throat increases on account of
both the increase in entropy through the shocks and the increasing flow
through the slots.  With the configuration of figure 5(b), a diffuser
minimum area 13 percent greater than the first throat area was found
sufficient to permit the attainment of a Mach number of 1.14.  With the
reduction in slot area and the provision of an essentially constant-
area mixing region provided by nose B the required area at the second
minimum was reduced to a value 9 percent greater than that at the first.
Because of the thick boundary layer, choking is not sharp at the second
minimum; but after Mach number 1.0 has been reached in the main stream,
the volume flow can still be increased by acceleration of the boundary
layer, though the cost in power rapidly becomes excessive.

Because of the larger minimum diffuser area required for the super-
sonic flow, the diffuser entrance area is greater than that required for

the subsonic flow. Since the flow attaches to the diffuser entrance
noses, a diffusion and consequent negative Mach number gradient occurs
upstream from the noses. This effect was sufficiently severe in the case
of nose shape B to require the provision of flaps which, when open, per-
mitted the entrained flow to pass over the noses and thus prevented
attachment of the main flow. Moreover, inasmuch as the diffuser entrance
area affects the diffusion, physical considerations would suggest that
the power required is also affected. Tests carried out by the Langley
24-inch tunnel section have shown this to be the case. An increase of
the diffuser minimum cross section appreciably beyond that just necessary
for the required Mach number results in an increase in the power required.
An increase in noise and vibration is also believed to be likely. It is
suggested that, in any future slotted tunnel installation similar to
that herein discussed, the effective diffuser entrance area be made
adjustable by means of radially adjustable diffuser entrance noses.

It was thought that the heavy boundary layer due to the inflow into
the slots might spoil the diffuser, but an extensive investigation by
means of tufts failed to reveal any separation, though separation may
have existed on the diffuser entrance noses. Because of the large
kinetic energy in that region, the possibility of significant power
loss near the diffuser entrance is greater than that farther downstream.

An examination of power data for varying slot area showed that, as
might be expected, the power required for a given Mach number is less,
the smaller the slot area. Lower power consumption is therefore also
favored if the diffuser entrance nose is as far upstream as possible.
This effect may be expected to become relatively less important as the
Mach number is increased, because the increasing required outflow through
the upstream part of the slots and the corresponding inflow at the
downstream ends is only weakly dependent on the slot area. It also
appears likely that with increasing inflow of this low-energy air the
essentially constant-area mixing region required for its acceleration
might have to be increased in order to prevent spoiling the diffuser
flow. Economy of power might indeed, at higher Mach numbers, require
that this low-energy air be pumped to approximately stream total pressure
by means of a separate compressor rather than by means of turbulent
mixing in the diffuser.

The power absorption per square foot of throat area in the Langley
8-foot high-speed tunnel is shown in figure 18. These data were taken
from a number of different runs as indicated in the figure. The power
data have been adjusted to the same stagnation pressure and temperatures
through the assumption that, for constant geometry and Mach number,
power is proportional to $H\sqrt{T}$, where $H$ is the stagnation pressure
and $T$ is the absolute value of the stagnation temperature. The power
for the slotted tunnel is compared with that for the Langley 8-foot

high-speed tunnel with slots closed, for the plaster nozzle of reference 2, and for a closed-tunnel estimate based on reference 5. The reduction in power due to the installation of diffuser entrance nose B (fig. 6(b)) is seen from a comparison of the power for this nose with that for nose A (fig. 6(a)).

## CONCLUSIONS

1. As the result of an investigation of the flow characteristics in a large slotted tunnel with various slot shapes, a configuration which produced closely uniform supersonic flow has been devised.

2. With this configuration the Mach number was continuously variable up to the greatest value, approximately 1.14, permitted by the power available; the quality of the flow compared favorably with that in the best two-dimensional solid supersonic nozzles.

3. The Mach number distribution was found to be affected by the detailed slot shape provided the divergence angle between the panels and the center line of the test section was sufficiently small.

4. The power required at a given Mach number was considerably in excess of that necessary for a closed tunnel at the same Mach number.

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    National Advisory Committee for Aeronautics
        Langley Field, Va.

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2. Ritchie, Virgil S., Wright, Ray H., and Tulin, Marshall P.: An 8-Foot Axisymmetrical Fixed Nozzle for Subsonic Mach Numbers up to 0.99 and for a Supersonic Mach Number of 1.2. NACA RM L50A03a, 1950.

3. Ward, Vernon G., Whitcomb, Charles F., and Pearson, Merwin D.: An NACA Transonic Test Section with Tapered Slots Tested at Mach Numbers to 1.26. NACA RM L50B14, 1950.

4. Nelson, William J., and Klevatt, Paul L.: Preliminary Investigation of Constant-Geometry, Variable Mach Number, Supersonic Tunnel with Porous Walls. NACA RM L50B01, 1950.

5. Goethert, Bernhard: Power Requirements and Maximum Reynolds Number in Transonic Wind Tunnels Having a Maximum Mach Number of 2.0. AAF TR No. 5564, Air Materiel Command, Army Air Forces, March 25, 1947.

Wall panel

Window

Section C-C

437

Section B-B

Section A-A
A

Test section
(50-in)
C

Diffuser
entrance nose

Tripod support system

Slots

Divergent slots
(96-in)

Slot width
approx const

Slotted region
(169-in)

A
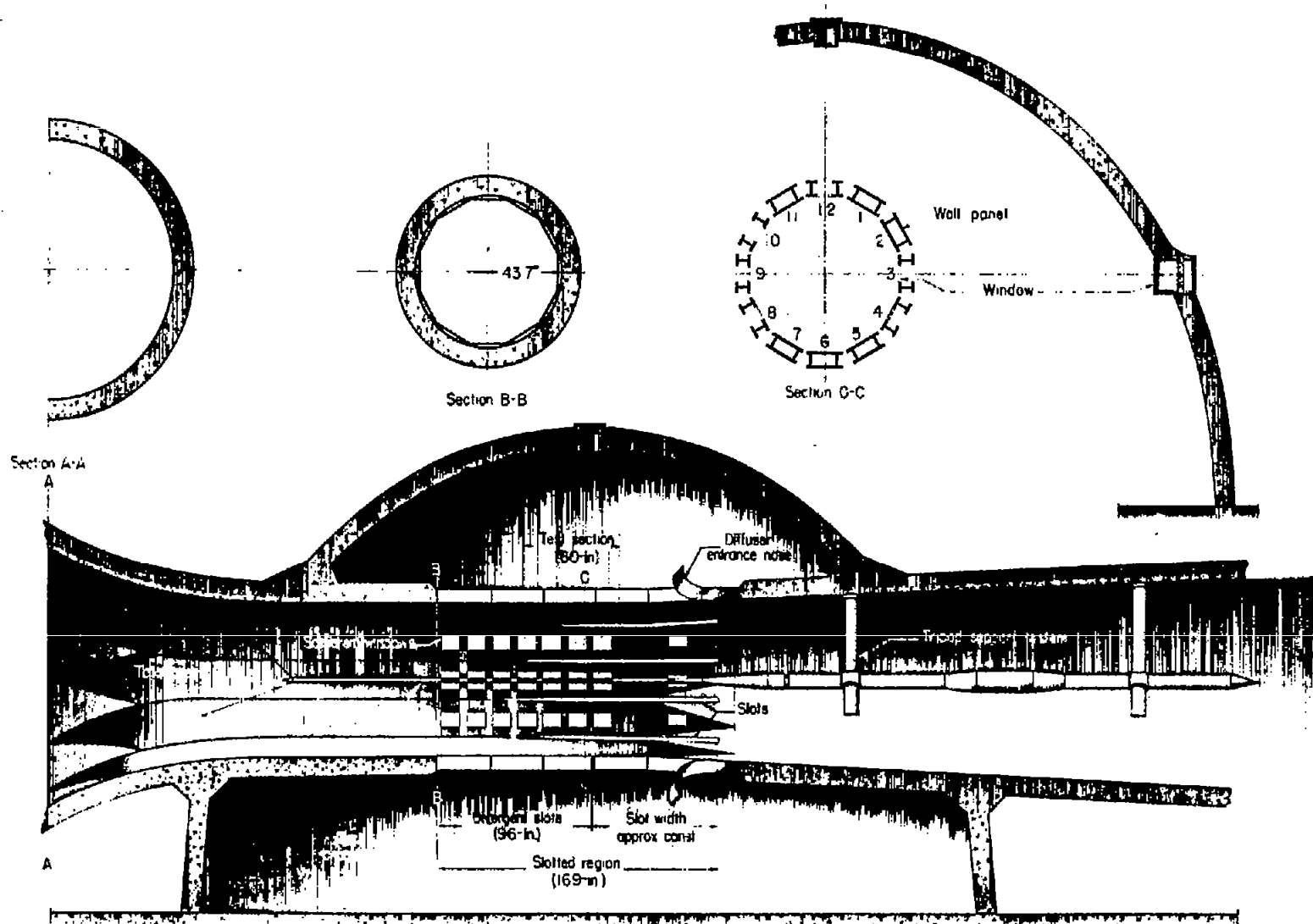
Figure 1.- Views of throat region of 8-foot high-speed tunnel showing
slotted test section, cylindrical survey tube, and support system.

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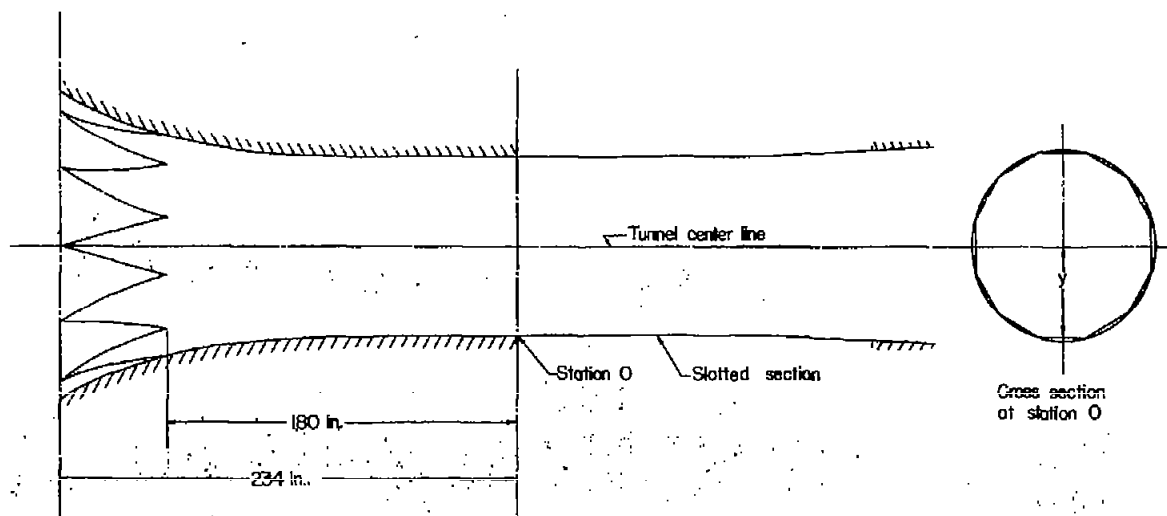
| x (in.) | y (in.) | | x (in.) | y (in.) | | x (in.) | y (in.) | | x (in.) | y (in.) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 43.700 | | 24 | 43.668 | | 48 | 43.685 | | 140 | 47.593 |
| 2 | 43.697 | | 26 | 43.666 | | 50 | 43.692 | | 150 | 48.882 |
| 4 | 43.694 | | 28 | 43.665 | | 55 | 43.715 | | 160 | 50.459 |
| 6 | 43.691 | | 30 | 43.664 | | 60 | 43.748 | | 170 | 52.365 |
| 8 | 43.688 | | 32 | 43.663 | | 65 | 43.793 | | 180 | 54.641 |
| 10 | 43.685 | | 34 | 43.663 | | 70 | 43.851 | | 190 | 57.333 |
| 12 | 43.682 | | 36 | 43.664 | | 80 | 44.018 | | 200 | 60.488 |
| 14 | 43.679 | | 38 | 43.665 | | 90 | 44.266 | | 210 | 64.480 |
| 16 | 43.677 | | 40 | 43.667 | | 100 | 44.618 | | 220 | 69.200 |
| 18 | 43.674 | | 42 | 43.670 | | 110 | 45.099 | | 228 | 73.680 |
| 20 | 43.672 | | 44 | 43.674 | | 120 | 45.735 | | 230 | 74.860 |
| 22 | 43.670 | | 46 | 43.679 | | 130 | 46.555 | | 234 | 77.188 |

x=Distance upstream of station 0
y=Distance from tunnel center line to center of panel

Figure 2.— Coordinates of approach to slotted region of the tunnel throat.
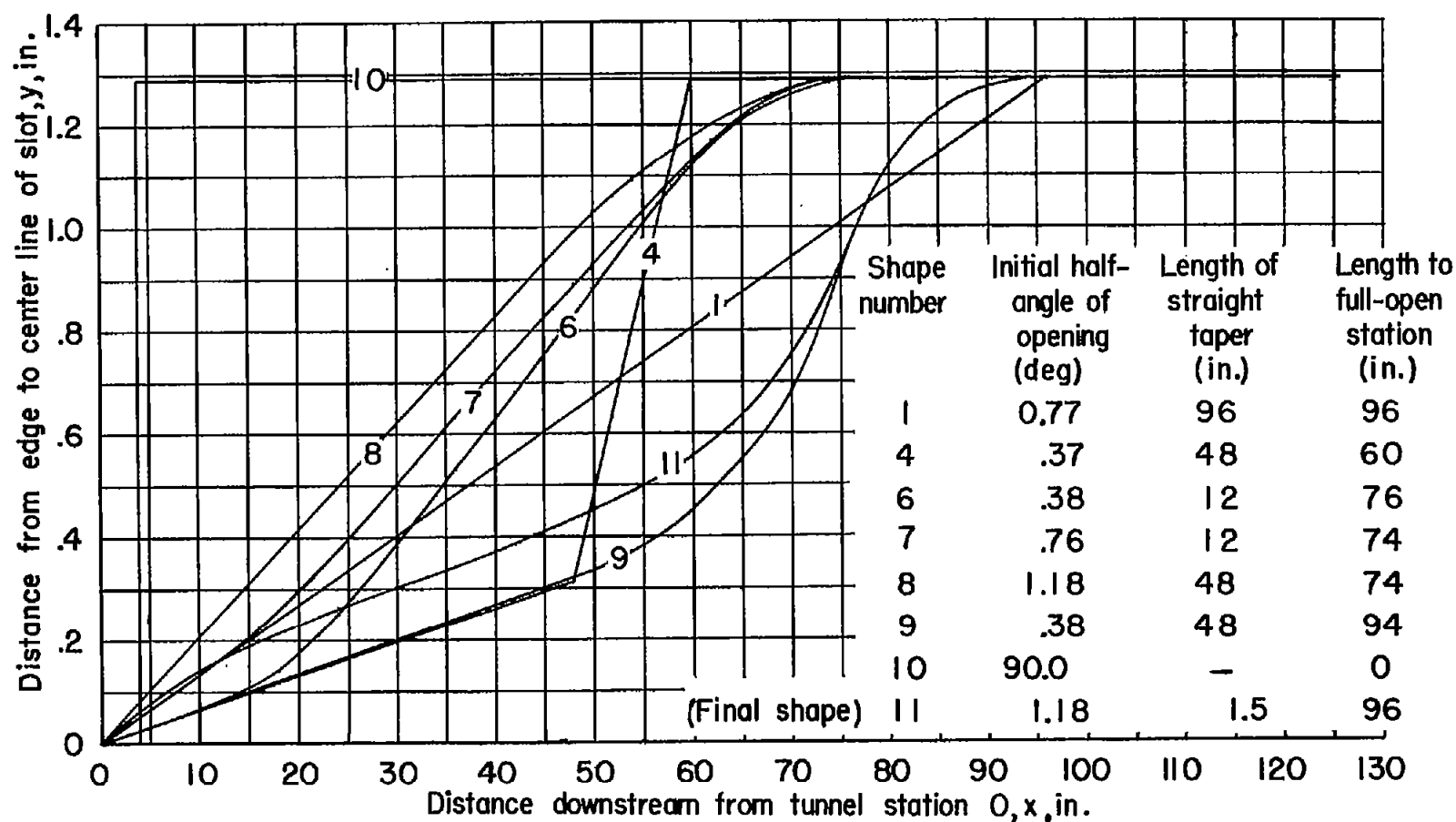
Figure 3.- Various slot shapes investigated in the Langley 8-foot high-speed tunnel with 5-minute wall-panel divergence in test section.
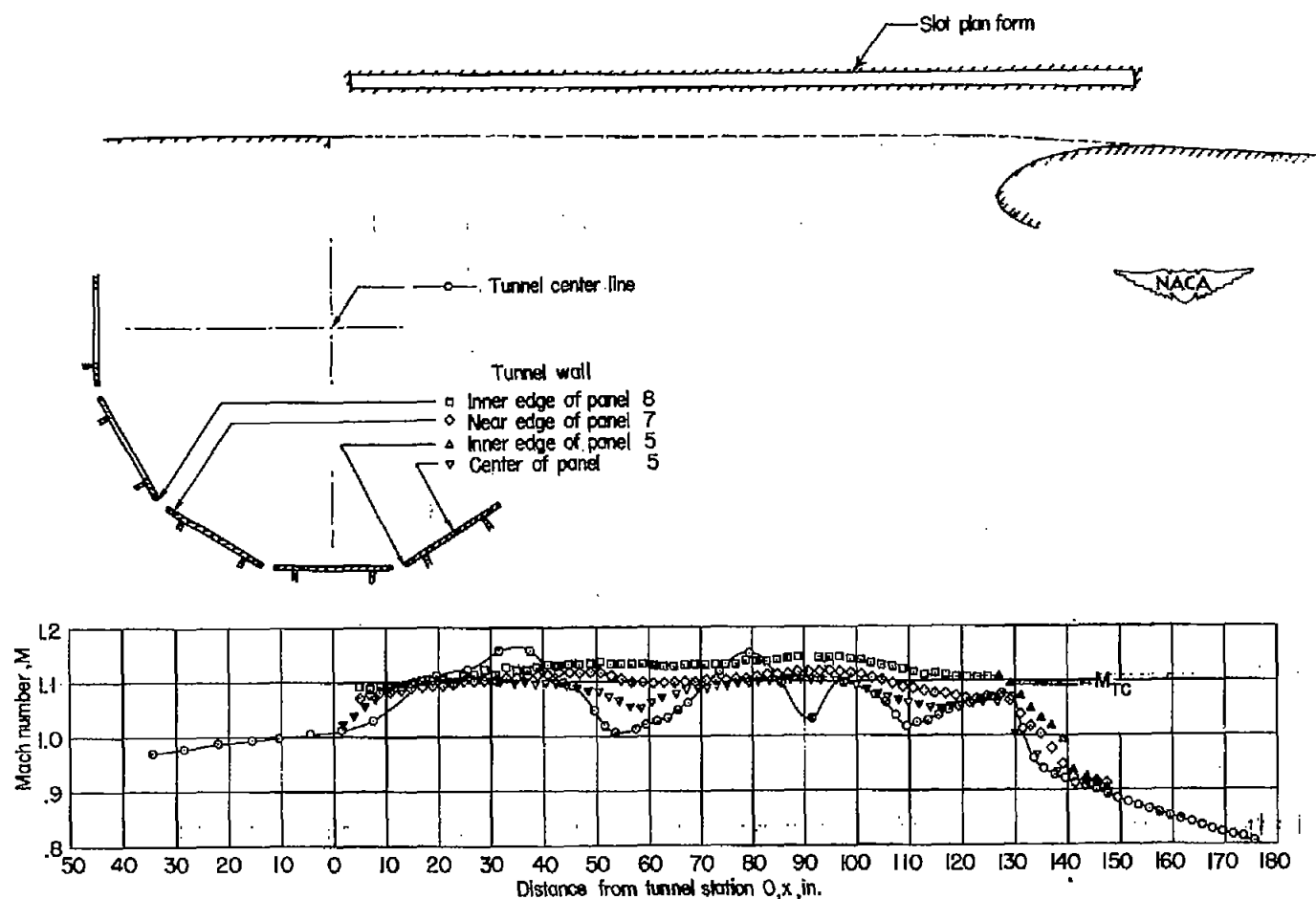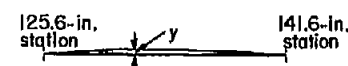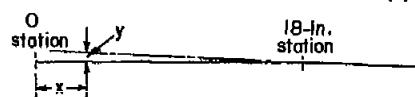
Figure 4.- Comparison of Mach number distributions measured axially
along tunnel center line with those measured along center and
edges of wall panels. Slot shape 10 (rectangular); 45-minute
divergence of wall panels in test section; Mach number corre-
sponding to test-chamber pressure, 1.092.

Diffuser entrance
nose

0
station

18-in.
station

125.6-in.
station

169-in.
station

180-in.
station

3°1'26"

←—Curved—→|←————————Straight, 45' divergence————————|←——Straight, 2°30' divergence——|

|←————————————————— Slotted region —————————————————|
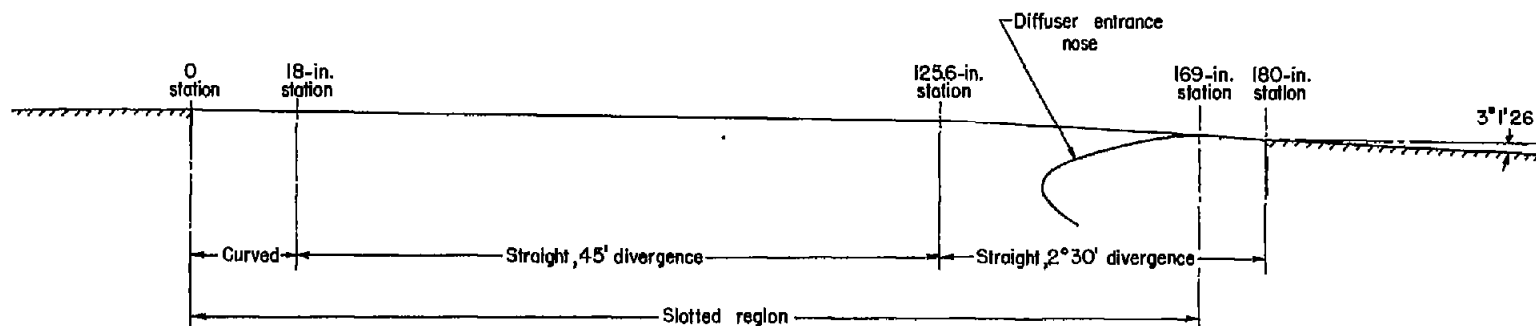
(a) Original wall-panel arrangement with 45-minute divergence in test section.

0
station

18-in.
station

125.6-in.
station

141.6-in.
station

COORDINATES OF CURVED REGION

COORDINATES FOR LINER

Liner

Diffuser entrance
nose

0
station

107-in.
station

125.6-in.
station

141.6-in.
station

169-in.
station

180-in.
station

3°1'26"

|←——————————— Straight, 5' divergence ———————————|←— Curved —→|←— Straight, 3°45' divergence —|

|←————————————————— Slotted region —————————————————|
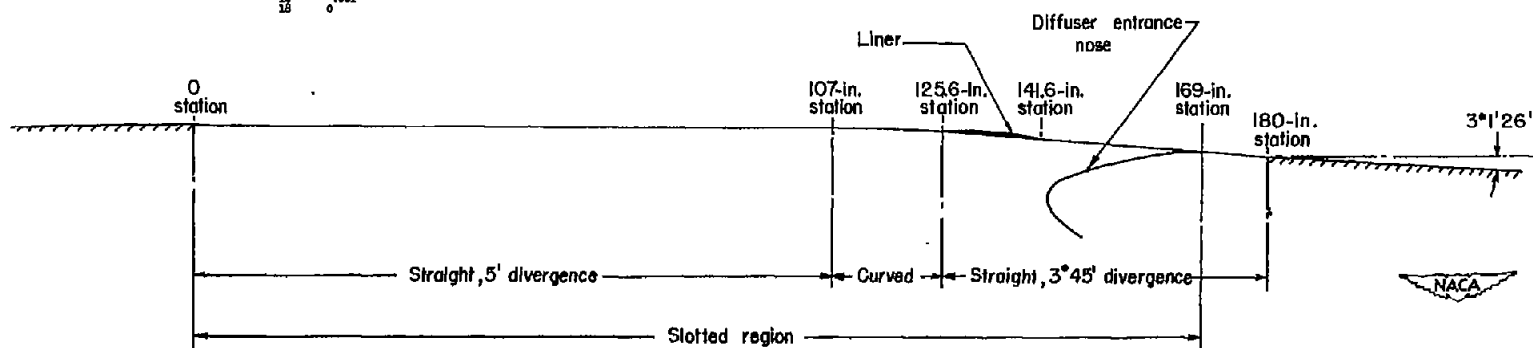
(b) Reversed wall panels with 5-minute divergence in test section.

Figure 5.- Tunnel throat geometry including diffuser-entrance nose shape
and wall divergence.

| x (in) | y (in) | y' (in.) | x (in.) | y (in.) | y' (in.) | x (in.) | y (in.) | x (in.) | y (in.) |
|--------|--------|----------|---------|---------|----------|---------|---------|---------|---------|
| 142.55 | 0 | 0 | 149 | 4.21 | 6.72 | 156 | 6.05 | 163 | 7.12 |
| 143 | 1.31 | 1.70 | 150 | 4.51 | – | 157 | 6.28 | 164 | 7.23 |
| 144 | 2.17 | 3.05 | 151 | 4.81 | – | 158 | 6.43 | 165 | 7.26 |
| 145 | 2.71 | 4.00 | 152 | 5.12 | – | 159 | 6.62 | 166 | 7.38 |
| 146 | 3.14 | 4.78 | 153 | 5.39 | – | 160 | 6.79 | 167 | 7.44 |
| 147 | 3.50 | 5.49 | 154 | 5.62 | – | 161 | 6.92 | 168 | 7.50 |
| 148 | 3.87 | 6.13 | 155 | 5.88 | – | 162 | 7.04 | 169 | 7.59 |

x=Distance downstream of station 0
y=Distance from diffuser-entrance-nose reference line to inner surface
y'=Distance from diffuser-entrance-nose reference line to outer surface

(a) Shape A.

Figure 6.- Coordinates of diffuser-entrance nose shapes.
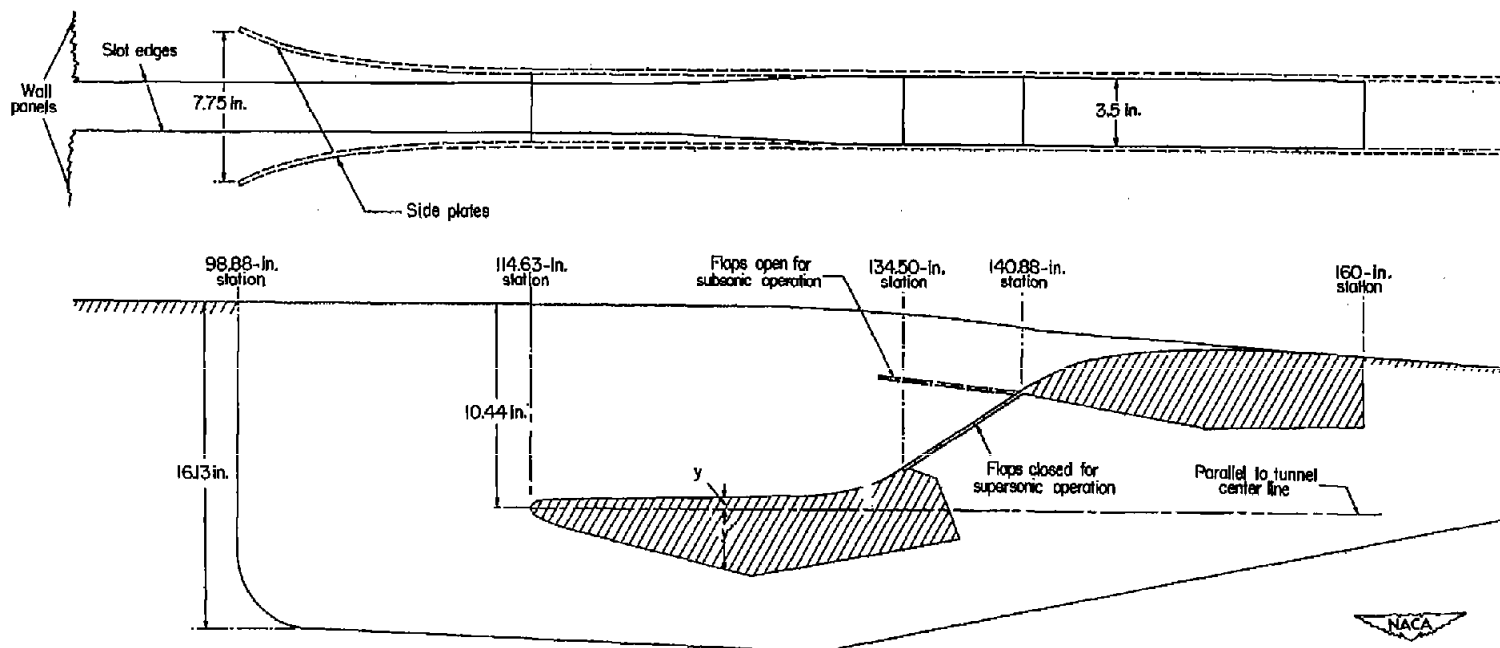
| x (in.) | y (in.) | y' (in.) | x (in.) | y (in.) | y' (in.) | x (in.) | y (in.) |
|---|---|---|---|---|---|---|---|
| 114.63 | 0 | 0 | 126 | .65 | 3.33 | 146 | 8.00 |
| 115. | .42 | .47 | 128 | .71 | 3.82 | 148 | 8.20 |
| 115.50 | .47 | .67 | 130 | .82 | – | 150 | 8.29 |
| 116 | .48 | .85 | 132 | 1.07 | – | 152 | 8.31 |
| 118 | .52 | 1.36 | 134.50 | 2.12 | – | 154 | 8.30 |
| 120 | .55 | 1.86 | 140.88 | 6.30 | – | 156 | 8.28 |
| 122 | .59 | 2.33 | 142 | 6.66 | – | 158 | 8.15 |
| 124 | .62 | 2.83 | 144 | 7.58 | – | 160 | 8.03 |

x = Distance downstream of station O
y = Distance from diffuser-entrance-nose reference line to inner surface
y' = Distance from diffuser-entrance-nose reference line to outer surface

(b) Shape B.

Figure 6.- Concluded.
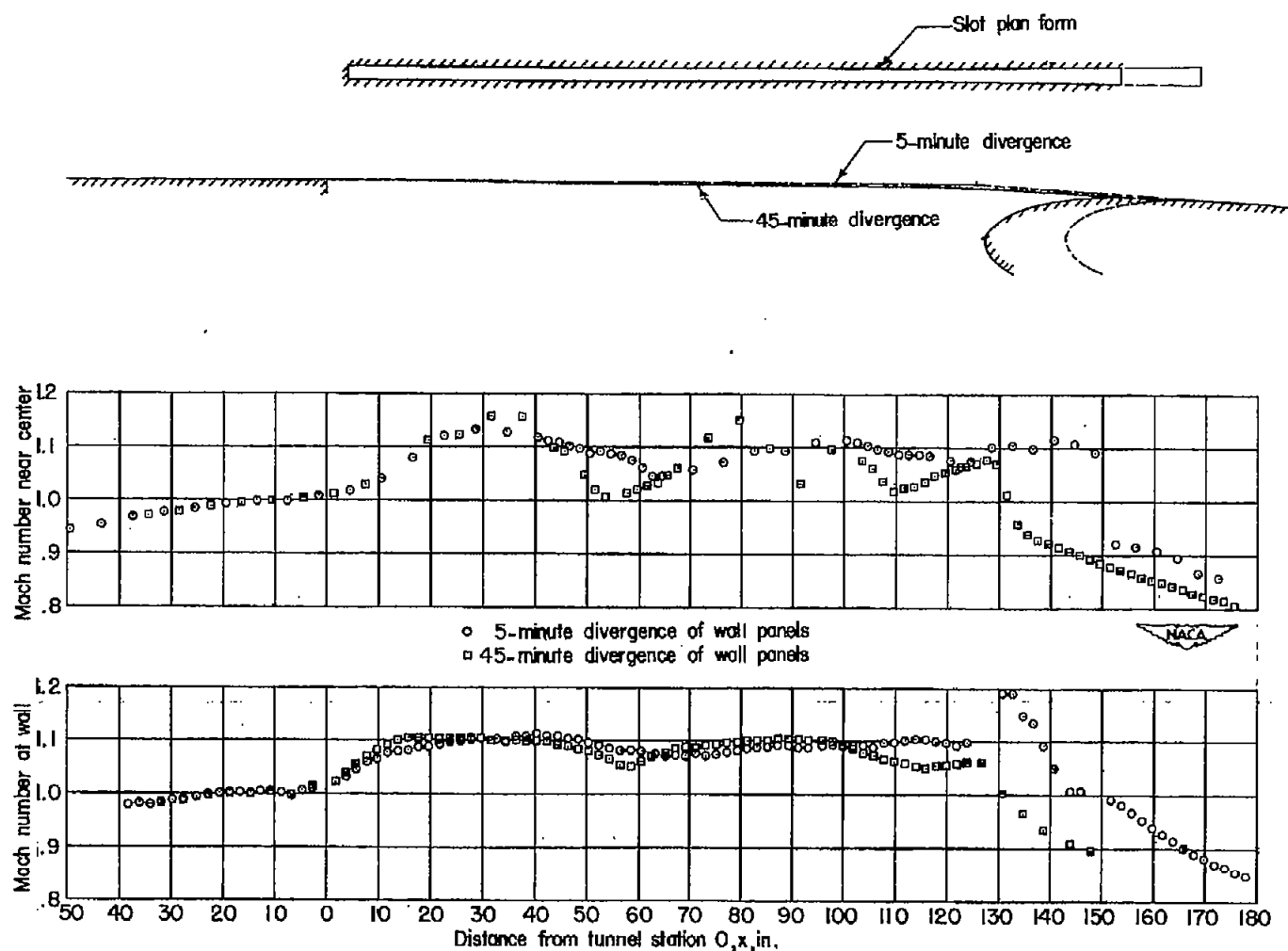
Figure 7.- Comparison of Mach number distributions axially along center line and wall in throat region with 5-minute and 45-minute divergence of wall panels in slotted test sections. Slot shape 10. $M_{TC} = 1.093$.
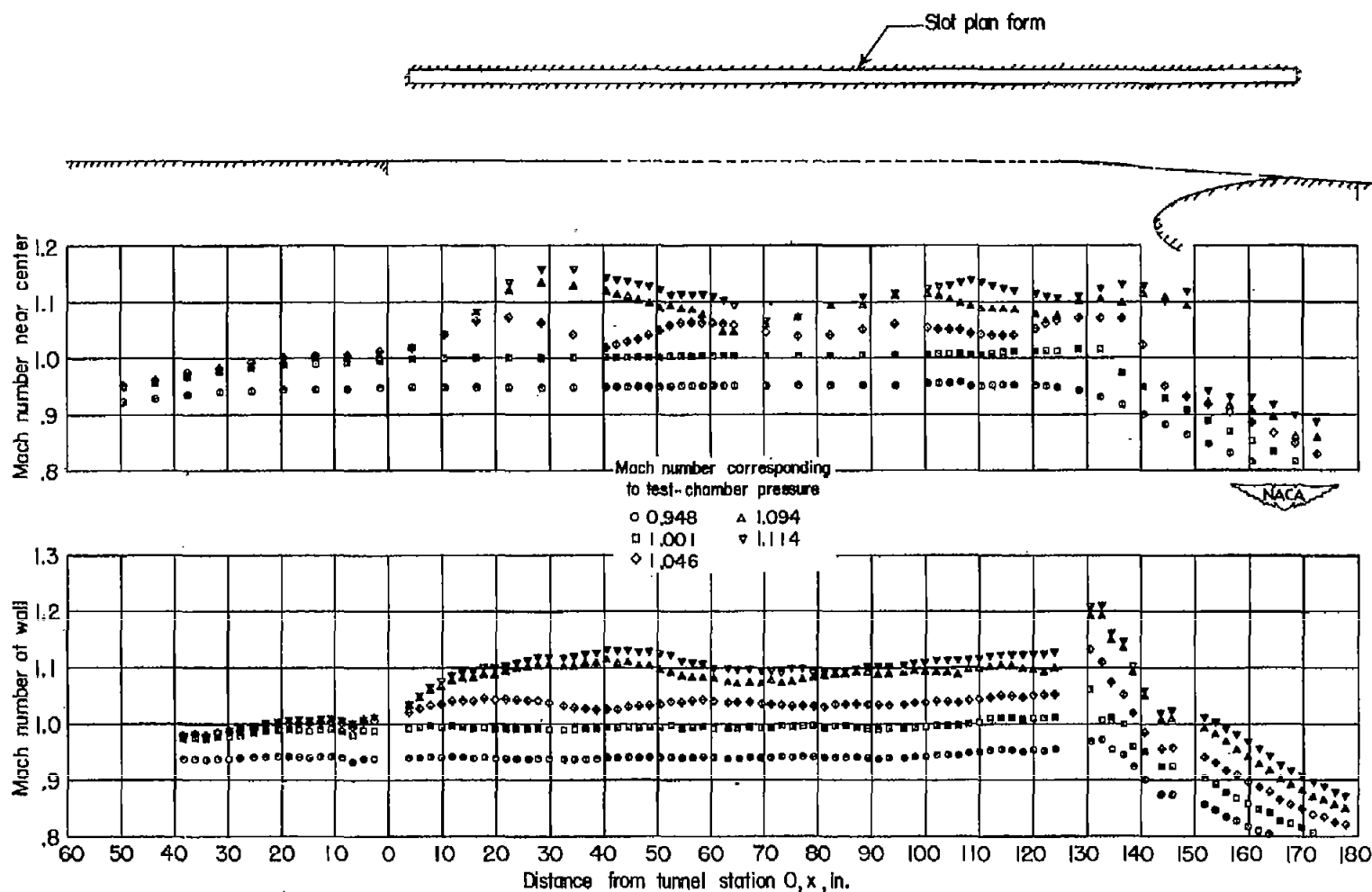
Figure 8.- Mach number distributions axially along wall and near center line of the slotted throat with 5-minute divergence of test-section wall panels. Slot shape 10.
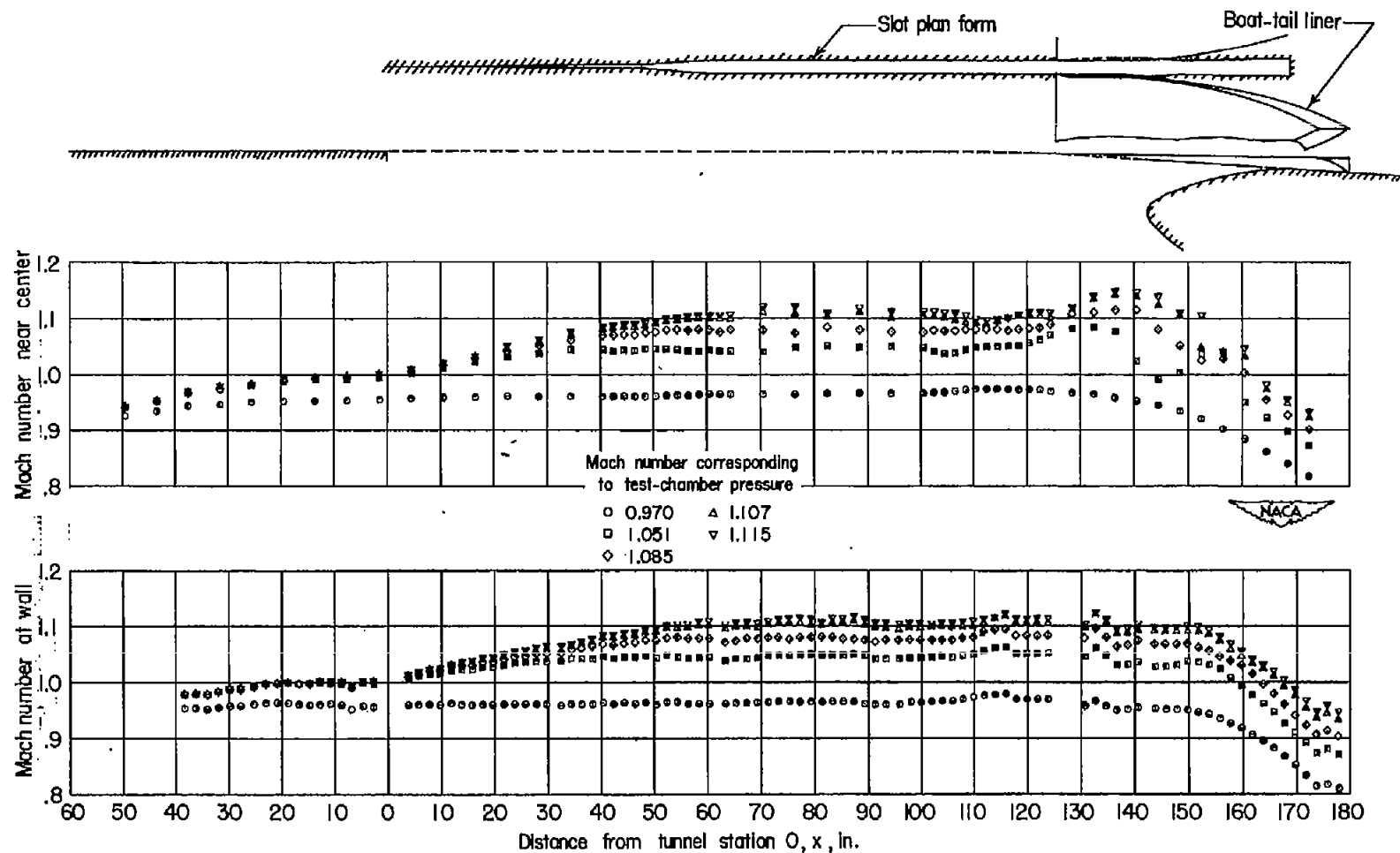
Slot plan form

Boat-tail liner

Mach number corresponding
to test-chamber pressure

| | | |
|---|---|---|
| ○ 0.982 | ▲ 1.113 | |
| □ 1.059 | ▽ 1.123 | |
| ◇ 1.091 | | |

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Distance from tunnel station 0, x, in.
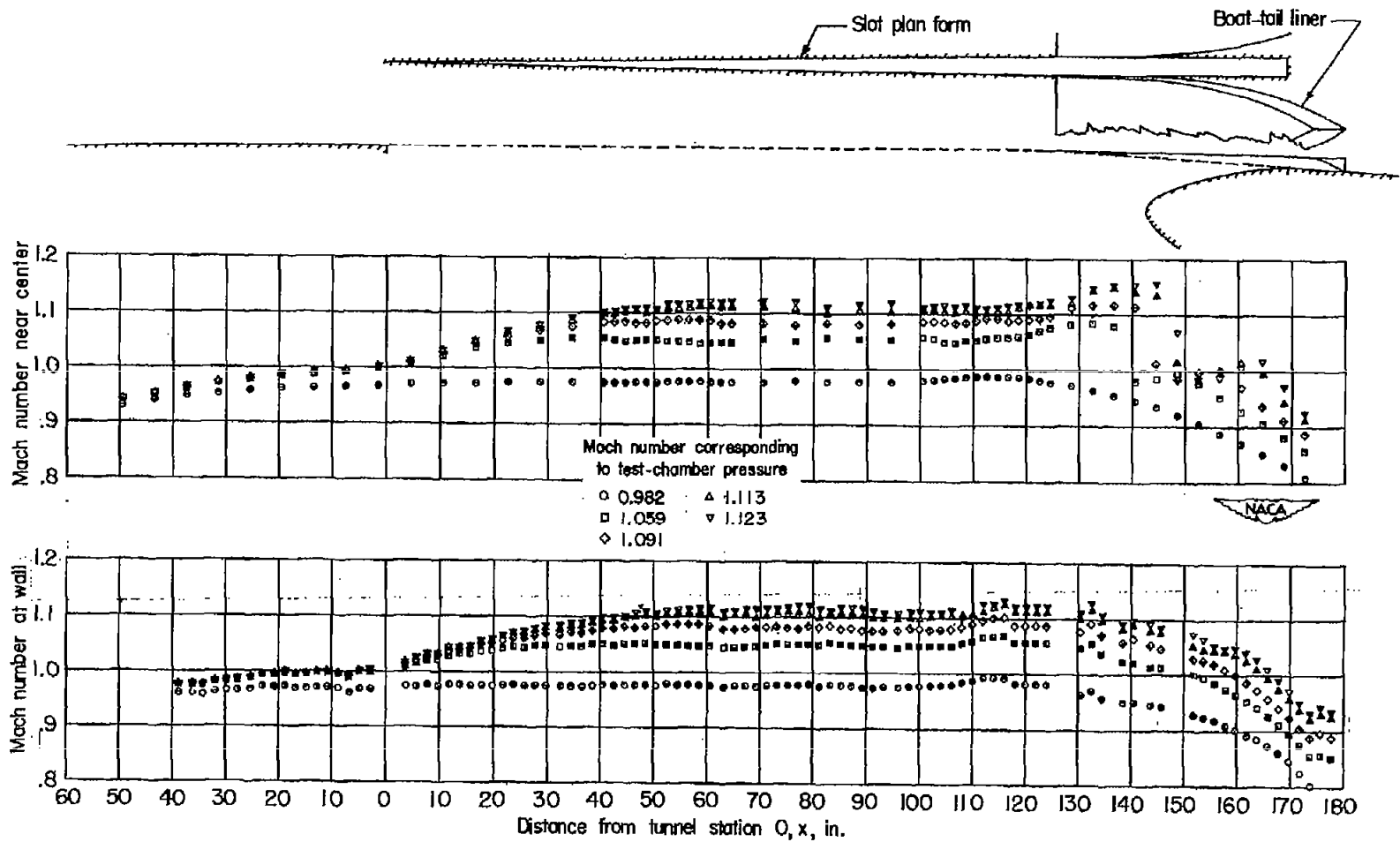
Figure 9.- Mach number distributions axially along wall and near center
line of the slotted throat with 5-minute divergence of test-section
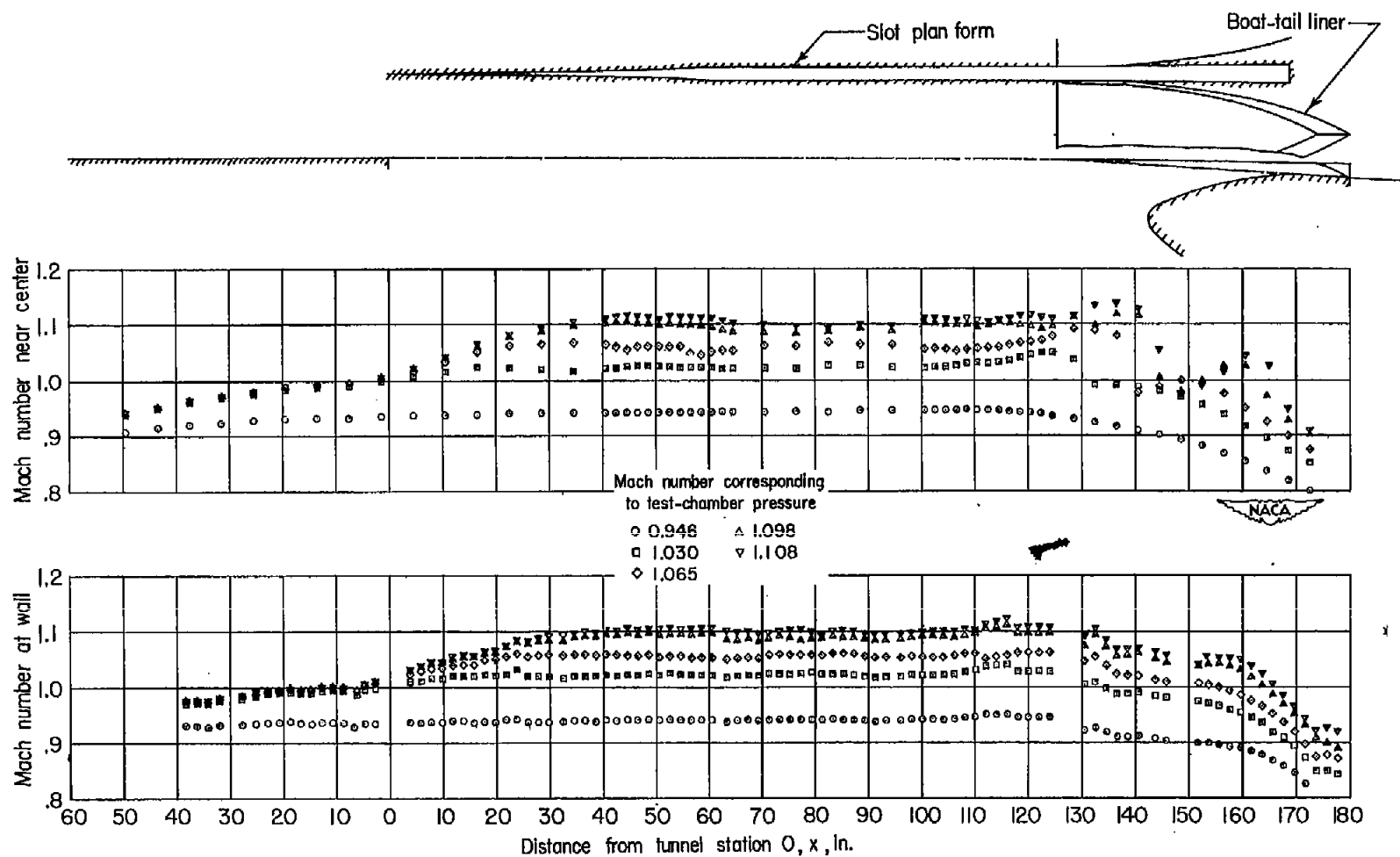wall panels. Slot shape 1.

Figure 10.- Mach number distributions axially along wall and near center
line of the slotted throat with 5-minute divergence of test-section
wall panels. Slot shape 4.
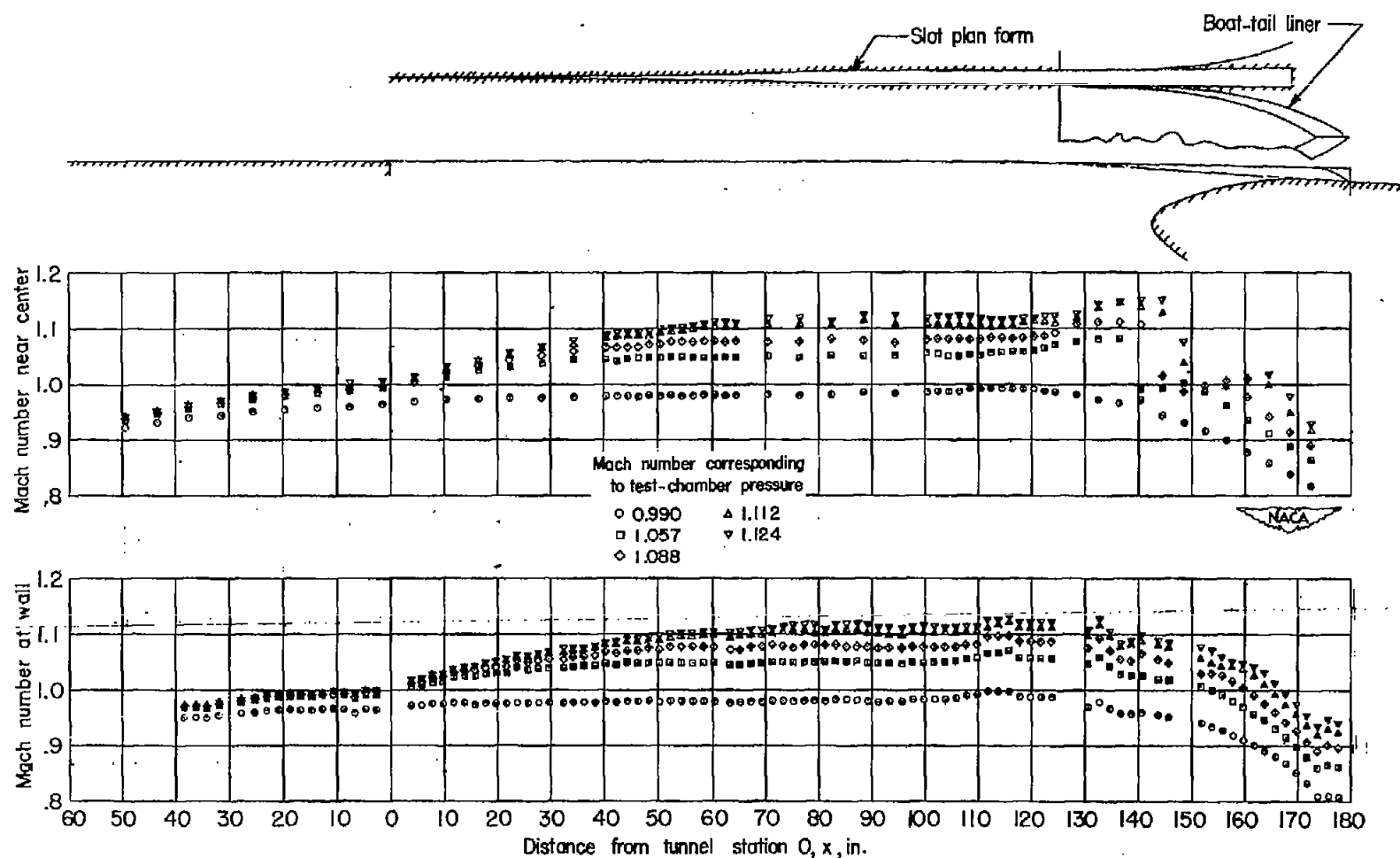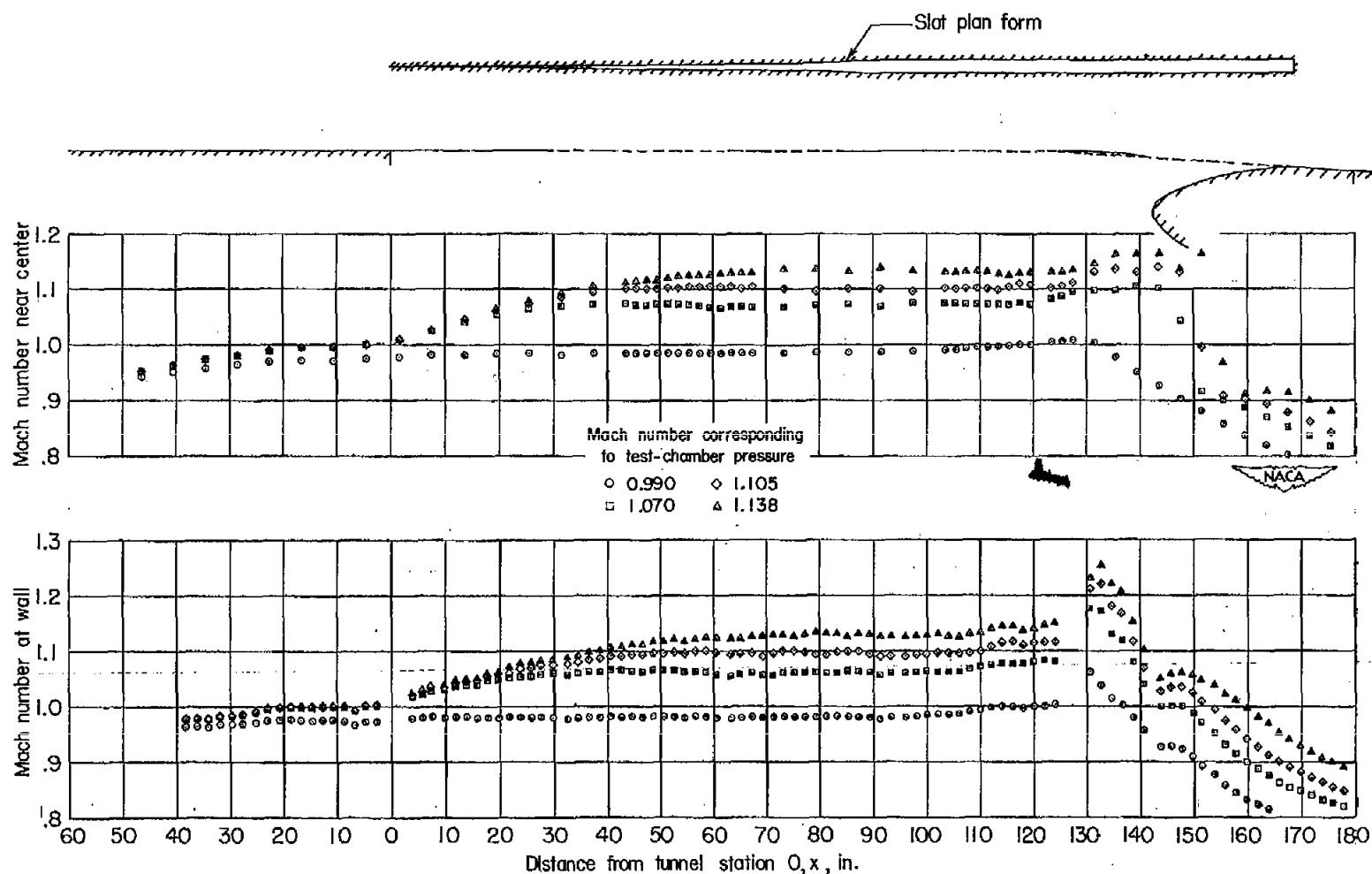
Figure 11.- Mach number distributions axially along wall and near center
line of the slotted throat with 5-minute divergence of test-section
wall panels. Slot shape 9.
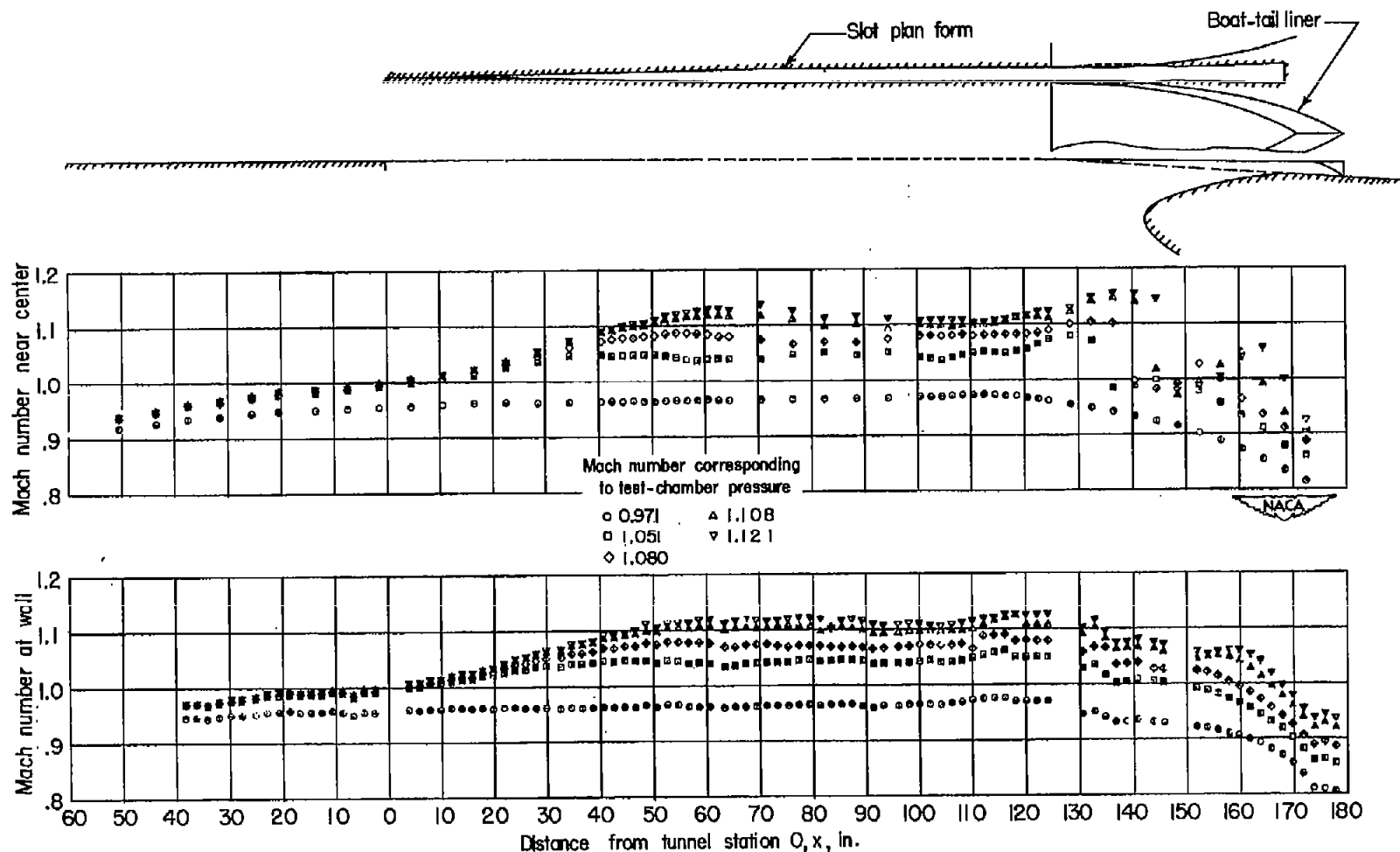
Figure 12.- Mach number distributions axially along wall and near center
line of the slotted throat with 5-minute divergence of test-section
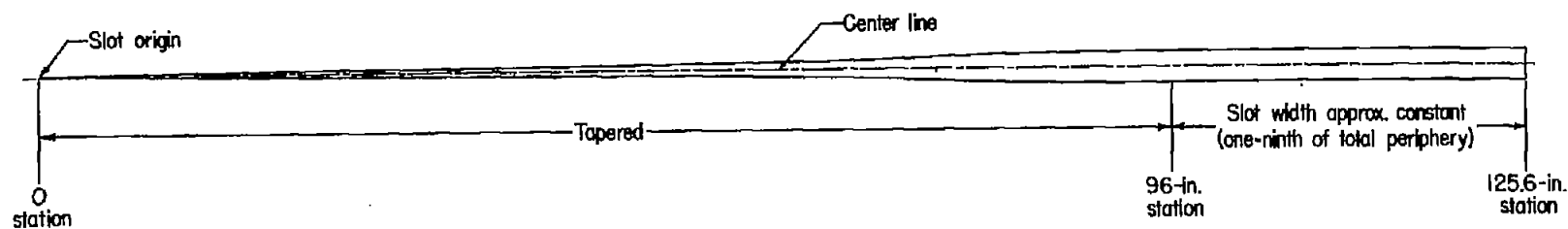wall panels.  Slot shape 6.
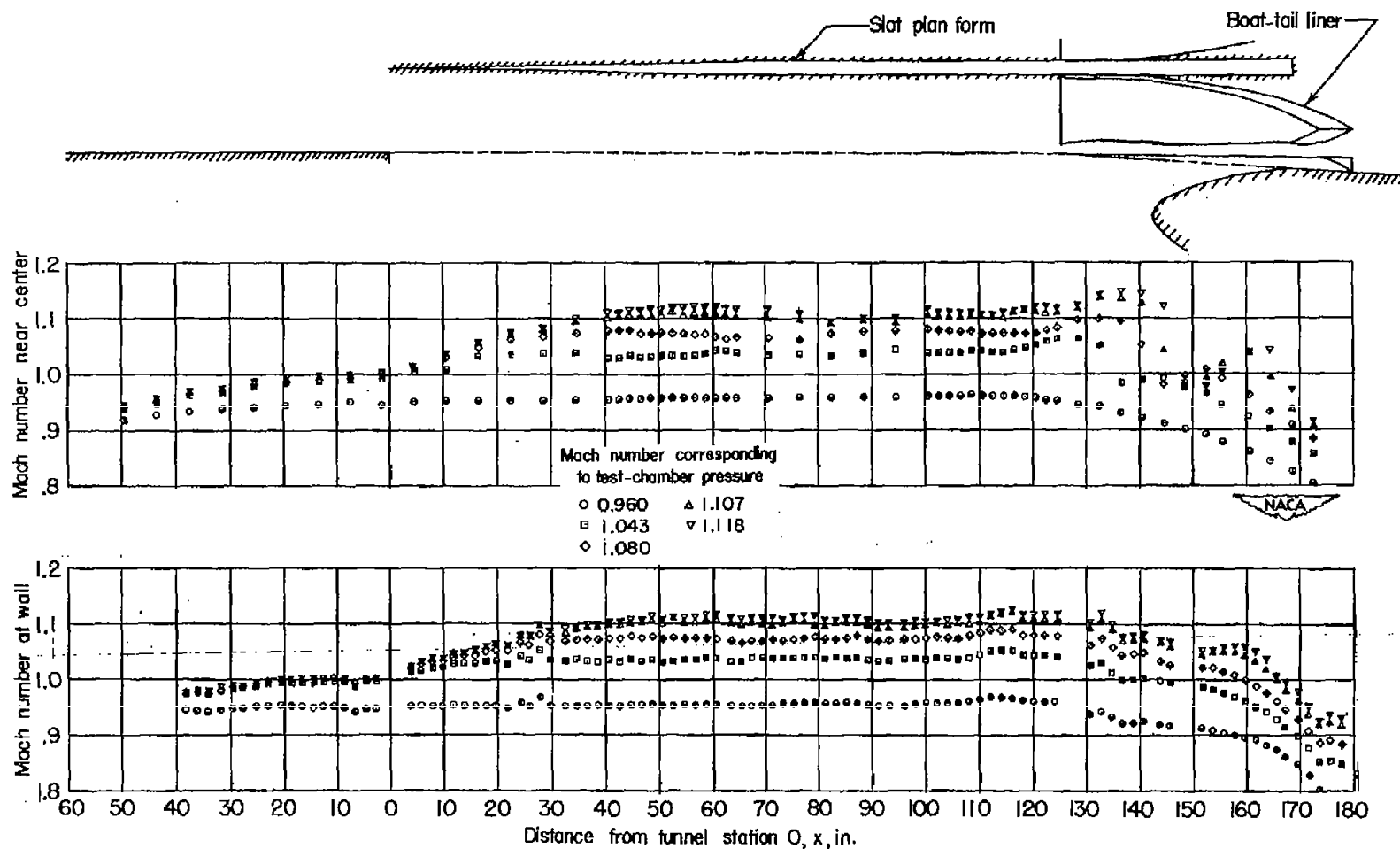
Figure 13.- Mach number distributions axially along wall and near center
line of the slotted throat with 5-minute divergence of test-section
wall panels. Slot shape 7.

Figure 14.- Mach number distributions axially along wall and near center
line of the slotted throat with 5-minute divergence of test-section
wall panels.  Slot shape 8.

Figure 15.- Mach number distributions axially along wall and near center
line of the slotted throat with 5-minute divergence of test-section
wall panels.  Slot shape 11.

Figure 16.- Coordinates of final slot shape developed for use in the Langley 8-foot high-speed tunnel.

| x (in.) | y (in.) | x (in.) | y (in.) | x (in.) | y (in.) | x (in.) | y (in.) | x (in.) | y (in.) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 20 | .233 | 40 | .371 | 60 | .556 | 80 | 1.120 |
| 2 | .037 | 22 | .250 | 42 | .386 | 62 | .585 | 82 | 1.170 |
| 4 | .068 | 24 | .263 | 44 | .403 | 64 | .618 | 84 | 1.210 |
| 6 | .098 | 26 | .278 | 46 | .418 | 66 | .656 | 86 | 1.240 |
| 8 | .122 | 28 | .290 | 48 | .433 | 68 | .700 | 88 | 1.260 |
| 10 | .144 | 30 | .303 | 50 | .451 | 70 | .751 | 90 | 1.273 |
| 12 | .165 | 32 | .316 | 52 | .469 | 72 | .812 | 92 | 1.281 |
| 14 | .185 | 34 | .329 | 54 | .486 | 74 | .882 | 94 | 1.288 |
| 16 | .202 | 36 | .343 | 56 | .508 | 76 | .969 | 96 | 1.290 |
| 18 | .219 | 38 | .356 | 58 | .530 | 78 | 1.060 | 125.6 | 1.291 |

x = Distance downstream of slot origin
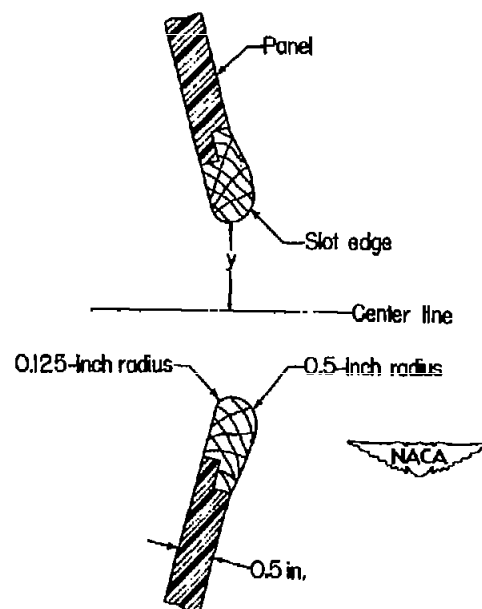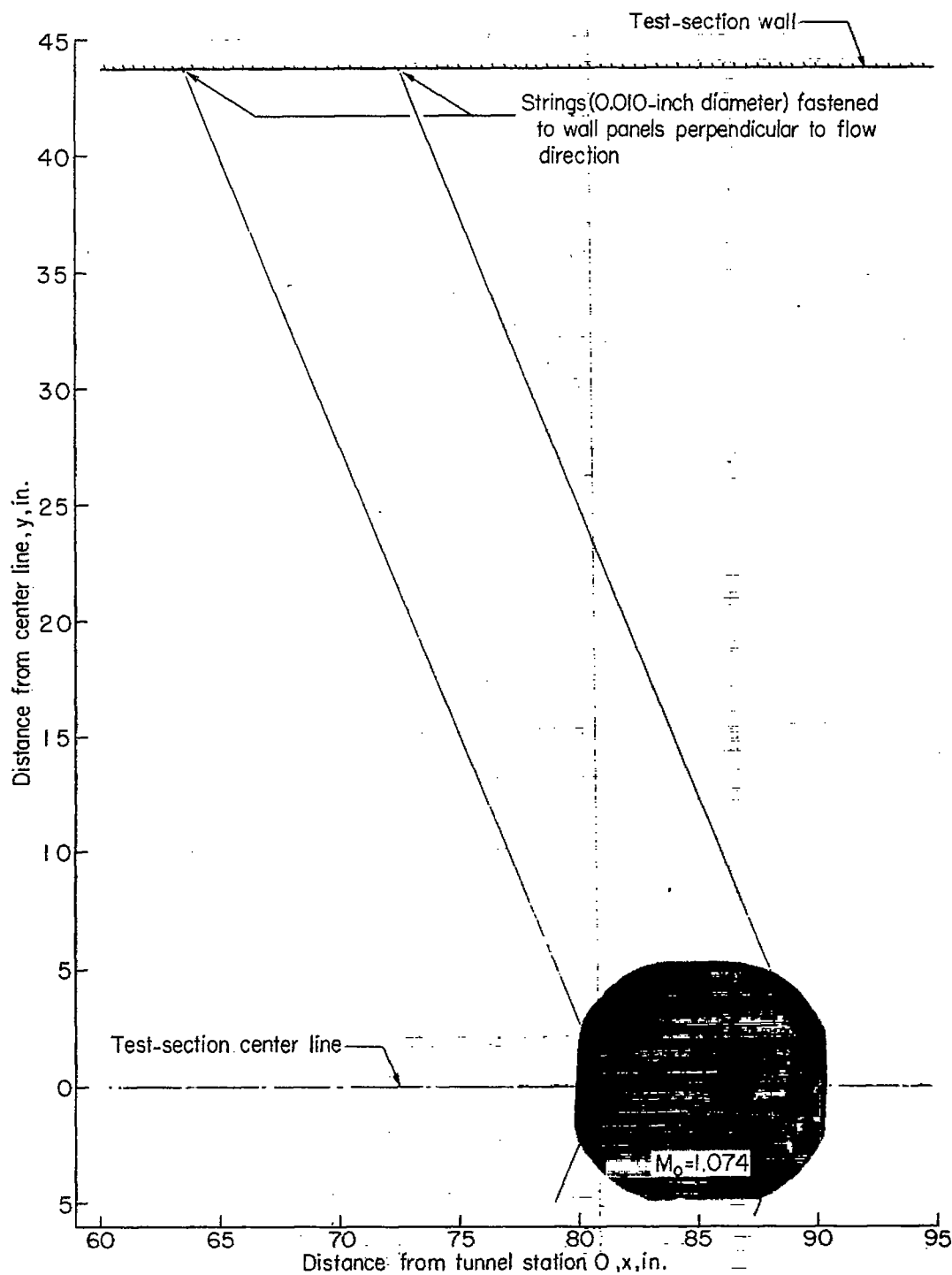y = Distance from slot edge to center line

Figure 17.- Schlieren picture illustrating the propagation of weak disturbances in supersonic flow in the slotted test section. $M_0 = 1.074$.
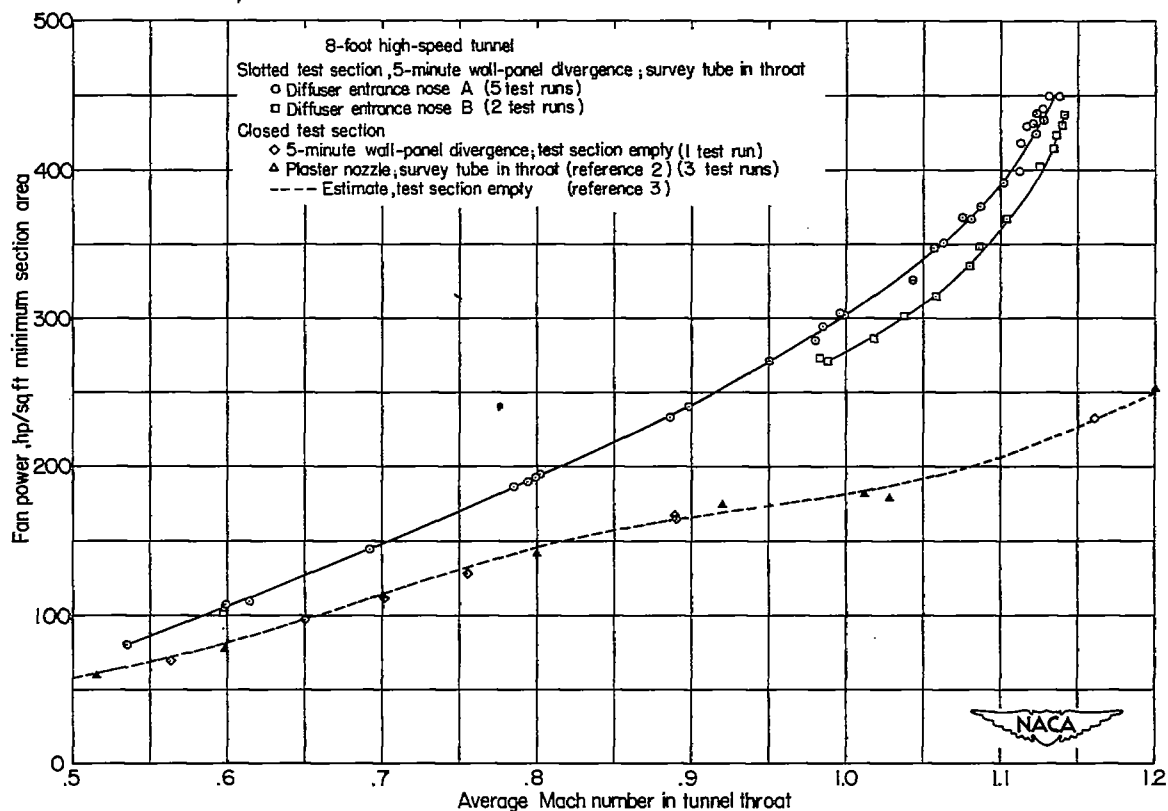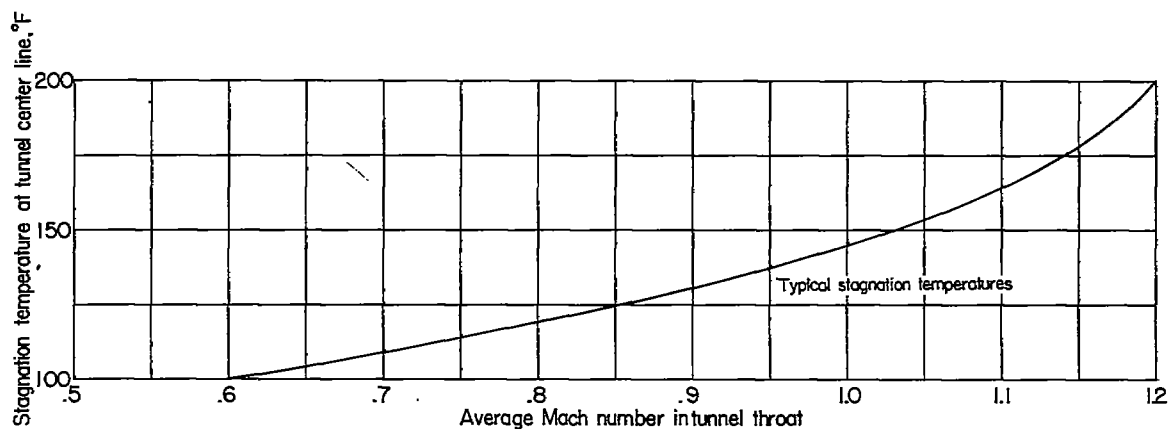
Figure 18.- Power requirements for transonic operation of wind tunnel with closed and slotted test sections. All power data reduced to typical stagnation temperatures shown and to stagnation pressure of 2120 pounds per square foot.